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LIFE CYCLE SUSTAINABILITY ASSESSMENT

# The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment

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**Abstract**
*Purpose* In life cycle assessment (LCA), resource availability is currently evaluated by means of models based on depletion time, surplus energy, etc. Economic aspects influencing the security of supply and affecting availability of resources for human use are neglected. The aim of this work is the development of a new model for the assessment of resource provision capability from an economic angle, complementing existing LCA models. The inclusion of criteria affecting the economic system enables an identification of potential supply risks associated with resource use. In step with actual practice, such an assessment provides added value compared to conventional (environmental) resource assessment within LCA. Analysis of resource availability including economic information is of major importance to sustain industrial production.
*Methods* New impact categories and characterization models are developed for the assessment of economic resource availability based on existing LCA methodology and terminology. A single score result can be calculated providing information about the economic resource scarcity potential (ESP) of different resources. Based on a life cycle perspective, the supply risk associated with resource use can be assessed, and bottlenecks within the supply chain can be identified. The analysis can be conducted in connection with existing LCA procedures and in line with current resource assessment practice and facilitates easy implementation on an organizational level.
*Results and discussion* A portfolio of 17 metals is assessed based on different impact categories. Different impact factors are calculated, enabling identification of high-risk metals. Furthermore, a comparison of ESP and abiotic depletion potential (ADP) is conducted. Availability of resources differs significantly when economic aspects are taken into account in addition to geologic availability. Resources assumed uncritical based on ADP results, such as rare earths, turn out to be associated with high supply risks.
*Conclusions* The model developed in this work allows for a more realistic assessment of resource availability beyond geologic finiteness. The new impact categories provide organizations with a practical measure to identify supply risks associated with resources. The assessment delivers a basis for developing appropriate mitigation measures and for increasing resilience towards supply disruptions. By including an economic dimension into resource availability assessment, a contribution towards life cycle sustainability assessment (LCSA) is achieved.

**Keywords** Economic criteria · LCA · LCSA · Resource availability · Scarcity · Supply risk

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## 1 Introduction

Access to resources "is often seen as a precondition for economic development" (UNEP 2010), and analysis of resource availability is of major importance to secure future supply (the

term resources as used in this paper refers to geologic resources, raw materials, materials and energy carriers). A frequently applied method for the assessment of resource use of products and product systems is life cycle assessment (LCA). Within LCA, "resource provision capability for human welfare" (Udo de Haes et al. 2002; UNEP 2010) is defined as an area of protection (AoP), focusing on the removal of resources from the environment. By extracting resources, the concentration in the earth's crust is changed. However, if and to what extent biogeochemical cycles are affected and if potentially environmental changes occur due to resource depletion itself (and not the extraction) is not clear (Sala 2012). As resources have often rather an instrumental (availability for human use) than an environmental value, distinction between environmental and economic aspects of resource depletion is often not straightforward (Steen 2006; Udo de Haes et al. 2002; Weidema et al. 2005).

Even though resource depletion is not always seen as a true "environmental impact" and inclusion in environmental assessment is questioned (Finnveden 2005; UNEP 2010), evaluation of resource use and availability is common practice within LCA (European Commission 2010b; ISO 2006a, b). Existing models for the assessment of resource availability in LCA relate to energy and mass of a resource used, exergy or entropy impacts, future consequences of resource extraction (e.g., surplus energy, marginal cost), and diminishing geologic deposits, or assess environmental impacts of resource extraction (see i.a. BUWAL 1998; Finnveden et al. 2009; Goedkoop and Spriensma 2001; Guinée 2002; Hauschild and Wenzel 1998; Klinglmair et al. 2013; PE International 2012; Steen 2006; Stewart and Weidema 2005; van Oers et al. 2002).

However, these models focus on geologic finiteness and deliver no conclusion about actual resource availability at the site of production. Resources commonly perceived as scarce are not visible in the results (e.g., rare earth metals are up to this point of no relevance in the life cycle analysis of electric vehicles; Schneider et al. 2011b, 2013).

There are serious difficulties in defining the "problem" of resource depletion, and the lack of consensus leads to incongruent results. Especially in consideration of the fact that depletion or scarcity of resources can affect human productivity (Klinglmair et al. 2013; Weidema et al. 2005), a holistic and realistic assessment of resource use has to go beyond the analysis of mere (physical) availability of resources in the natural environment (Klinglmair et al. 2013) or the impacts of their extraction. A comprehensive analysis towards life cycle sustainability assessment (LCSA), including social and economic information, is needed to find more sustainable means of resource use.

The current AoP is used as a general category encompassing environmental considerations of resource depletion. However, a direct link to environmental consequences is missing. In fact, "resource provision capability for human welfare" is already aptly describing the general concern over the access to resources and the availability for human use, and implementation of the AoP needs to go beyond the current environmental focus and comprehensively address this issue. Supply risks concerning the continued resource provision capability ought to be assessed in addition to geologic availability. The focal point of the AoP needs to be extended to include limited supply (scarcity) of resources caused by economic (e.g., distributional or political) or social (e.g., human rights abuse) restraints or risks. The consideration of these additional dimensions complements existing models for the analysis of resources, as it goes beyond an environmental function towards the comprehensive assessment of resource availability in the context of LCSA.

In the present paper, criteria affecting economic systems (referred to as "economic criteria") and ultimately resources availability are assessed complementary to existing environmental LCA models to sustain industrial production and to increase resilience towards supply disruptions (Graedel and Erdmann 2012; UNEP 2010). Within this study, new impact categories for the assessment of resource provision capability from an economic angle are developed and implemented. These impact categories cover a broad range of economic availability criteria and are applied for a portfolio of 17 metals.

Various papers and working groups are dealing with criticality of resource supply, but independently from a life cycle-based approach (i.a. Angerer et al. 2009a, b; defra 2012; Erdmann and Behrendt 2010; European Commission 2010a; Graedel et al. 2012a; Nassar et al. 2012; National Research Council 2008; Rosenau-Tornow et al. 2009; VDI 2013). Several of these studies aim at developing and applying a methodology to determine resource criticality with regard to certain systems, and quantitative scales are introduced to compare the supply risk of resources. For the availability assessment of resources consumed in a product system including a life cycle perspective, these scales are not meaningful due to the low margin of results. This means results would be mainly influenced by the quantity of the resource used but not by the respective supply risk.

## 2 Economic resource availability

In Table 1 an overview of several criteria potentially affecting resource availability and supply is provided. By analyzing such economic criteria, supply risks can be identified, and more informed decisions regarding choice and use of resources can be made.

In Section 2.1, criteria influencing supply risk and respective indicators for quantification of these criteria as used in this work are described in more detail. Section 2.2 describes the methodology of the proposed model for the assessment of resource availability from an economic angle in more detail.

**Table 1** Exemplary overview of economic criteria potentially affecting resource supply

| | |
|---|---|
| Availability of reserves | Coproduction/companion metal fraction |
| Economic stability | Potential for substitution |
| Concentration of reserves or production to certain countries | Competing technologies |
| Concentration of production activities to certain companies | Demand growth/change rate of demand |
| Trade barriers | Logistic constraints |
| Volatility | Availability of (exploitable) anthropogenic stocks |
| Price elasticity of demand and supply | Capacity utilization |
| Recycling/availability of secondary material | Availability of energy carriers |
| Societal acceptance of mining activities | Dissipative use of resources |
| Susceptibility to natural disasters | Investment in mining |
| Transportation costs | Production costs |

### 2.1 Criteria and indicators

The criteria and indicator selection in this work takes up and complements existing works (see i.a. Erdmann and Behrendt 2010; Erdmann and Graedel 2011; European Commission 2010a; Graedel et al. 2012a; National Research Council 2008; Rosenau-Tornow et al. 2009; Yellishetty et al. 2011). All described criteria might affect the supply security of resources and consequently cause supply shortages. Regarding the selection of criteria and indicators for quantification, data availability proves to be the main limiting factor. Even though choice of criteria and indicators should be as broad as possible, several criteria have to be neglected at present as data availability and quality is poor (e.g., regarding the availability of anthropogenic stocks or potential for substitution). Chosen indicators are based on publicly available and accepted databases or publications. In the following paragraphs, indicators as used in this work are introduced in more detail.

*Reserves* have a physical as well as an economic dimension. Per definition of the USGS, reserves are "that part of a resource which could be economically extracted or produced at the time of determination" (USGS 2013) displaying current production technologies. Availability of resources can be assessed by means of the depletion time (reserve-to-production ratio). Even though the reserve-to-production ratio changes over time, it is a useful indicator to evaluate periodic availability of a resource (see, e.g., also Graedel et al. 2012b).

*Recycling* can be an efficient mechanism to secure supply (UNEP 2011). From a product perspective, primary metal consumption can be reduced by the use of secondary material, thus relieving pressure on virgin resource supplies (Graedel and Erdmann 2012). The recycled content is defined as the annual tonnage of material scrap consumed divided by the tonnage of material produced and depends on the amount of scrap available (European Commission 2010a; UNEP 2011). Thus, even with a high recycling rate, the recycled content can be low. The reverse of the recycled content, the new material content, indicates how much primary material is used in the production of a specific material on an average basis. As primary supply (as evaluated in this study) is subject to restrictions, the new material content provides a good reference for determination of supply risk.

A high *concentration* of one activity (e.g., mining) in few countries or a limited number of companies is always associated with a high risk regarding the accessibility of a resource. The assessment of country or company concentration is relevant at all stages of the supply chain. The Herfindahl-Hirschman Index (HHI) is a common measure of market concentration. The indicator is calculated by squaring the market share of each company or country with regard to the production/reserves and the summation of the results (von der Lippe 1993) (see also, e.g., Graedel et al. 2012b; Rosenau-Tornow et al. 2009).

*Economic stability* refers to risks related to policies, regulations, social progress, etc., that can have an effect on resource availability. Even though focus of this indicator is on overall investment and not on supply security of resources in specific (Rosenau-Tornow et al. 2009), the Worldwide Governance Indicators (WGI) are used as an approximation to model stability of governance processes of different countries (The World Bank Group 2012). As economic stability is dependent also on human development, in addition, the Human Development Index (HDI) is evaluated and included in the assessment for describing socioeconomic stability of different countries (Graedel et al. 2012a; UNDP 2011). The corresponding indicator represents a statistic for life expectancy, education, and income referring to social and economic development (UNDP 2011).

*Demand growth* can be assessed by means of past and future trends—based on future technologies, average annual growth rates, etc. Demand growth can be used to indicate potential pressure on timely supply. In this study, annual growth rates for the resources are considered. If available, future demand scenarios are included in the calculation of the indicator (Angerer et al. 2009a; USGS 2005, 2013).

*Trade barriers* are government-induced restrictions on international trade by means of, e.g., export quotas, taxes, tariffs, etc., leading to increasing prices or physical shortages of resources. The respective indicator represents the percentage of production of a certain resource underlying barriers. Any potential barrier to trade is considered (including tariff and nontariff measures) (BDI 2010).

*Companion metal fraction* describes the supply risk associated with resources that depend on the magnitude of mining of carrier or "host" metals (Graedel et al. 2012a; Graedel and Erdmann 2012). Availability of companion metals is strongly

dependent on the demand for the carrier metal as companion metals cannot be mined economically by themselves. The interconnectivity of resources plays an important role in the determination of supply risk associated with individual resources due to complex pricing and technical limits to adapt production (Hagelüken and Meskers 2010; Reuter et al. 2005). Carrier metals are in general considered to be less vulnerable to supply risk than companion metals. Thus, as an indicator the percentage of a metal mined as companion metal is used to assess potential supply risk. As limited data is available, default values were also used based on data published by Erdmann and Behrendt (2010).

To what extent these criteria affect availability of individual resources and pose a threat to continued supply is assessed within this work. An analysis of interrelations of individual criteria is out of the scope of this work but will be included in future studies.

Many of the assessed indicators should be considered at several stages of the supply chain. Economic constraints can occur at any production stage (e.g., mining, refining, or distribution). In the present paper, for simplification and due to limited data availability, only the mine production (raw material stage) is assessed. In further works, an assessment of these other supply chain stages needs to be included to cover all potential restrictions and risks associated with the supply of materials like copper or steel (e.g., over 70 % of the seaborne trade of iron is controlled by three companies only, resulting in high company concentration for traded iron; European Commission 2010a; UNCTAD 2012). In the next section, the methodological framework of the new model introduced in this paper is described.

### 2.2 Economic impact assessment methodology

For the assessment of economic resource availability, the discussed criteria are transferred into impact categories which are described by characterization models using an analogy to LCA and current life cycle impact assessment (LCIA) methodology. In Table 2, an overview of these impact categories and corresponding category indicators, constituting the core of the characterization model, is presented.

In the context of the assessment of resource availability from a supply risk perspective, a measure to quantify the contribution to the supply risk needs to be included in the characterization model. The category indicator needs to be placed in relation to a target that facilitates an evaluation of risk. Hence, a similar formula as specified in the ecological scarcity method (a "distance-to-target" method) is used by including a threshold or "scale of risk" into the modeling (Frischknecht et al. 2009; Hischier and Weidema 2010; Müller-Wenk 1978). The resulting impact factors ($I$) are a function of current indicator values and the threshold above which high risk of supply is expected. These factors are calculated for each resource ($i$) and each impact category ($j$).

For calculation of the impact factors, the ratio of the current to the critical flow is squared: this means the major exceeding of the target value (implying high risks) is weighted above proportional (see Eq. (1)) (Frischknecht et al. 2009). All indicators are scaled to the range 0 to 1. When needed, order is inverted, such that a higher score corresponds to a high risk (similar to existing methods within LCA). To avoid compensation during further aggregation of impact factors, no values below "1" are permitted in the assessment.

$$I_{i,j} = \mathrm{Max}\left\{ \left( \frac{\text{indicator value}_{i,j}}{\text{threshold}_{i,j}} \right)^2 ; 1 \right\} \tag{1}$$

Resulting supply risk associated with resources is a dimensionless quantity determined exclusively by the ratio of the current indicator value to the determined threshold linked to the life cycle inventory (LCI) (see also Frischknecht et al. 2009). Category indicator results (impact factor × LCI) give an indication about the magnitude of the risk (exceeding of threshold related to the amount of the resources). However, only a comparison of different resources can provide a meaningful estimation of associated supply risks and a basis for decision making. For that purpose and for comparison with conventional resource assessment methods, the different impact categories can be combined to a single "economic resource scarcity potential" (ESP) for each resource, enabling a ranking of overall risk. For calculation of the ESP, impact factors are aggregated using multiplication (see Eq. (2)). A summation of factors would lead to the same ranking, but the relative differences of results would be smaller. As this model will be linked with an LCI that might be dominated by few resources, impact factors need to have a significant margin, so results are not determined only by the specific quantity of resources used.

$$\mathrm{ESP}_i = \prod_j \left( I_{i,j} \right) \tag{2}$$

Aggregation, as used in this work, implies equal weighting of individual impact factors. This approach can of course be modified as weighting might prove useful with regard to an emphasis of individual aspects or to avoid overvaluation of aspects. While there is controversial discussion about the application of weighting, in the here assessed context regarding the analysis of supply risk of resources independently from LCA, the applied method is meaningful.

### 2.3 Definition of threshold

The risk threshold provides the advantage of an easy interpretation of results. In Table 3, an overview of thresholds used in

**Table 2** Overview of impact categories and indicators

| Impact category | Description | Category indicators |
|---|---|---|
| Reserve availability | Depletion time (displaying current production technologies) | Reserve-to-annual-production ratio |
| Recycling | Recycled content of a resource | New material content (%); data as published by UNEP (2011) |
| Country concentration reserves | Reserve concentration in certain countries | HHI—index is calculated by squaring the market share of each company or country with regard to the production or reserves (USGS 2013) and the summation of the results; |
| Country concentration mine production | Concentration of mine production in certain countries | |
| Company concentration mine production | Concentration of mine production in certain companies | |
| Governance stability | Stability of governance in producing countries (mine production) | WGI—including key dimensions of governance (The World Bank Group 2012) (in this work, an aggregated indicator is used, based on three of the published dimensions that show only very low correlation: voice and accountability, political stability and absence of violence and government effectiveness; aggregation is based on equal weighting) |
| Socioeconomic stability | Human development in producing countries (mine production) | HDI—combining indicators of life expectancy, educational attainment and income; indicator as published by UNDP (2011) |
| Demand growth | Increase of demand (past and future) | Percentage annual growth based on past systematics (for basic industrial metals) and future demand scenarios (driven by future technologies) (see Angerer et al. 2009a and Rosenau-Tornow et al. 2009) |
| Trade barriers mine production | Raw materials underlying trade barriers | Percentage share of mine production under trade barriers; based on data as published by BDI (2010) |
| Companion metal fraction | Occurrence as companion metal within host metal ore bodies | Percentage of production as companion metal—host metals are copper, aluminum, iron, rare earths, nickel, zinc, lead, magnesium, titanium and tin. Based on data by Hagelüken and Meskers (2010), Reuter et al. (2005), and Erdmann and Behrendt (2010). |

this work is given. A threshold above which supply risk is expected is defined for each category indicator. The supply risk for the individual resources is then calculated based on the respective distance to this threshold.

Thresholds are highly system specific: An organization, with a large product portfolio and frequently changing products, would evaluate the risk of supply disruption as less critical than a company with few products and very long development and production life spans (e.g., vehicle production). Furthermore, products with long service lifetimes require stable availability of a required set of resources (Graedel and Erdmann 2012). Thus, even though vulnerability to supply disruptions is not included as a dimension in this work, it is considered implicitly by means of the system-specific determination of thresholds and perception of risk.

**Table 3** Determination of thresholds (exemplary, as used in this paper)

| Indicator | Threshold and risk |
|---|---|
| HHI | Low<0.15<high |
| WGI | Low<0.25<high |
| HDI | Low<0.12<high |
| Demand growth (%) | Low<0.01<high |
| Production under trade barriers (%) | Low<0.25<high |
| New material content (%) | Low<0.50<high |
| Companion metal fraction (%) | Low<0.20<high |
| Depletion time | Low>40>high |

Thresholds are based on data by DOJ and FDT (2010), The World Bank Group (2012), UNDP (2011), Rosenau-Tornow et al. (2009), and Daimler AG, 2012, personal communication

The system under study in this paper is the average "global economy." Thus, supply risk is determined as the average global risk. Thresholds are defined based on a general perception of risk in literature and current best practice in industry (Daimler AG, 2012, personal communication; DOJ and FDT 2010; Oryx Stainless 2012; The World Bank Group 2012; UNDP 2011). Setting of thresholds determines the impact factor and thus influences the ESP. To uncover all potential risks, a conservative approach is chosen in this work, and thresholds are selected which are not easy to attain (resulting in a high "distance to the targets").

Results of the aggregated ESP are highly sensitive to the choice of impact categories and indicators as well as to the definition of the risk threshold. Results of the assessment are system specific, and interpretation or comparison of results outside the system has little informative value. The assessment should not be regarded as fixed, situations should be regularly monitored, and indicators have to be updated and thresholds readjusted (see also Rosenau-Tornow et al. 2009).

## 3 Results

A portfolio of 17 metals is selected based on data availability and also reflecting conducted case studies (Oryx Stainless 2012; Schneider et al. 2011b). In current LCA studies, availability of resources for products or production systems is commonly assessed by means of the abiotic depletion potential (ADP) (CML 2013; Guinée 2002; van Oers et al. 2002). The method is recommended in the Dutch LCA handbook and in the Product Environmental Footprint (PEF) document of the European Commission as current best available practice for assessing resource availability (European Commission 2011, 2013; Guinée 2002). Even though enhancements of this method are published (see Schneider et al. 2011a), use of the conventional ADP is still mainstream practice. Hence, for the comparison of ESP results with commonly applied models, ADP results for the assessed metals are used as reference values. However, results of ADP and ESP are not directly comparable and shall be used complementary as the methods address different dimensions of resource availability.

In Fig. 1, the results of the $ESP_{global}$ are compared to the common $ADP_{ultimate\ reserve}$. The supply risk assessed by means of the $ESP_{global}$ is a dimensionless quantity (see Section 2.2). ADP results are a relative measure with the depletion of the element antimony as a reference (van Oers et al. 2002). The different methods lead to different conclusions. From a geologic perspective, gold is most critical, while rare earths and platinum group metals (PGMs) are associated with the overall highest supply risk.

The magnitude of the $ESP_{global}$ results is high, and any exceeding of the threshold implies a potential risk. Thus, in a second step, results are presented using a logarithmic scale to uncover the risk of all assessed metals (see Fig. 2). ADP results are adapted to fit a logarithmic scale for comparability of results. Based on the aggregated $ESP_{global}$ results presented in Fig. 2, the metals can be ranked according to their risk. For a different resource portfolio, other metals could be identified to bear the highest risk.

Resources delivering the highest $ESP_{global}$ are associated with the highest potential supply risk and thus indicate a need for action. Rare earths for example show a high supply risk in several categories resulting in potential constraints in resource supply. Similar results are found for PGMs. Contrary iron and nickel have low results across most impact categories leading to lower overall supply risk.

To further test and discuss validity of the proposed approach, results are compared qualitatively with supply risks identified in other studies (see Table 4). For this qualitative comparison, the divergence from the threshold in relation to the maximum possible values for individual impact categories is used as a basis. Resources with overall high divergence from these targets are evaluated as risky.

For all approaches, similar results are obtained. Deviations in results can be explained by the system under study, the choice and number of criteria and indicators or the temporal reference. Inclusion of additional indicators can increase or decrease overall supply risk for certain resources in comparison to the assessed resource portfolio. Within the ESP assessment, nickel has a lower relevance than in the study by Erdmann and Behrendt (2010) which could be caused by the consideration of additional categories like trade barriers that lower the relative supply risk of nickel in comparison to other resources in the assessed portfolio (see impact category results displayed in Fig. 3). Likewise, silver for example is evaluated as less risky by the European Commission (2010a) as only four indicators are considered, not including indicators where silver is associated with high supply risk (e.g., companion metal fraction or stability of producing countries). Low- and high-risk areas are only vaguely defined in the studies. A small shift in one of the indicators may result in an increase in overall supply risk and a shift from a low- to a high-risk area (see, e.g., chromium in the study of the European Commission 2010a).

While the ESP has a global focus, other studies assess resource availability for the European Union (European Commission 2010a) or Germany (Erdmann and Behrendt 2010). However, as supply risk is assessed by means of similar criteria within the different studies, the system perspective does not have an important effect on the results.

The comparison verifies that $ESP_{global}$ delivers a valid method and a good basis to comprehensively assess the supply

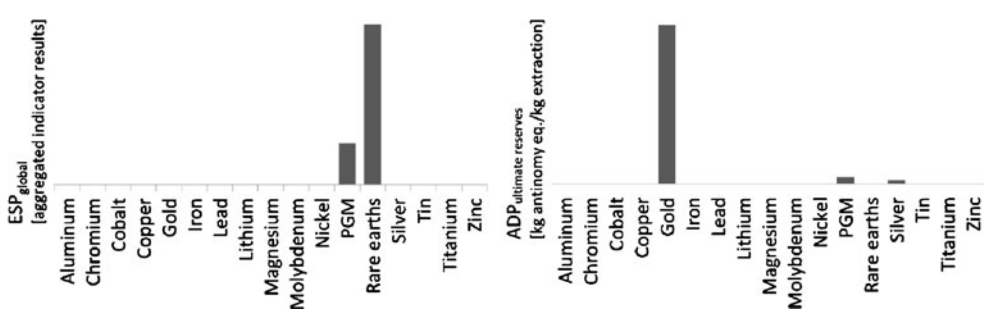


**Fig. 1** $ESP_{global}$* (*left*) vs. $ADP_{ultimate\ reserves}$** (*right*) (data based on CML 2013; Guinée 2002; PE International 2012; van Oers et al. 2002). *Regarding rare earth elements and platinum group metals (PGM), metal groups are assessed instead of individual metals. **For rare earths and PGM, always the raw material of the group with the highest $ADP_{ultimate\ reserves}$ is chosen for comparison

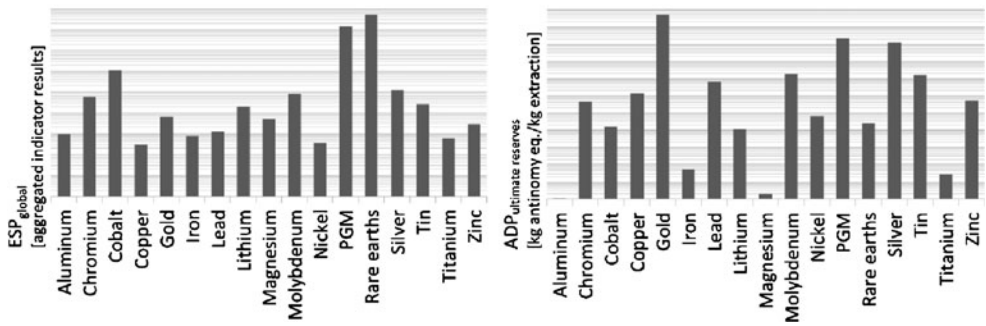


**Fig. 2** ESP$_{global}$ (*left*) vs. ADP$_{ultimate\ reserves}$ (*right*) (logarithmic scale)

risk associated with different resources. Results as displayed in Fig. 3 should be regarded as a basis for an analysis of individual impact category results of "risky metals" to identify hotspots and to develop appropriate strategies for risk mitigation (a logarithmic scaling is chosen due to the in parts high range of values of represented data).

## 4 Conclusions, challenges, and outlook

For sustainable development, an environmental, social, and economic dimension needs to be assessed. Within conventional LCA, resource use is considered from an environmental perspective. The social dimension of resource use is widely discussed, and tools (social LCA) (UNEP 2009b) and several studies exist (GHGm 2008; Kerkow et al. 2012; Tsurukawa et al. 2011) that are linked to the LCA framework. An assessment of economic resource availability considering a life cycle perspective was disregarded so far, and the economic dimension was mainly addressed from a financial perspective (e.g., life cycle costing) or concerning the efficient use of resources. As availability of resources depends on a broad set of economic criteria, this work provided a framework for the assessment of resource beyond existing models. For this purpose, impact categories for modeling the economic dimension of resource provision capability were developed analogously to existing LCA terminology and proceeding. As the new method can be applied in connection with existing life cycle-based approaches, easy implementation is facilitated. By introducing a procedure for the assessment of economic availability of resources, a contribution towards LCSA is made.

**Table 4** Qualitative comparison of supply risk as determined in major studies (studies are selected based on transparency of results)

| Resource | EU study (4)[a] (European Commission 2010a) | Yale study (6) (Nassar et al. 2012) | IZT study (6) (Erdmann and Behrendt 2010) | ESP$_{global}$[b] (9) |
|---|---|---|---|---|
| Aluminum | Low | | Low | Low |
| Chromium | Low | | High | Medium |
| Cobalt | High | | Medium | High |
| Copper | Low | Low | Medium | Low |
| Gold | | Low | | Low |
| Iron | Low | | Low | Low |
| Lead | | | Low | Low |
| Lithium | Low | | Medium | Medium |
| Magnesium | Low | | Low | Low |
| Molybdenum | Low | | Medium | Medium |
| Nickel | Low | | Medium | Low |
| PGM | High | | High | High |
| Rare earths | High | | High | High |
| Silver | Low | High | High | High |
| Tin | | | High | Medium |
| Titanium | Low | | Low | Low |
| Zinc | Low | | Medium | Low |

[a] The number in brackets indicates the number of indicators used to determine the supply risk

[b] The basis for this qualitative evaluation is the summarized divergence from the threshold value in relation to the maximum possible value across all impact categories (percent)

Availability of resources differs significantly when economic aspects are taken into account rather than geologic depletion. Detailed assessment of economic criteria influencing resource availability on a product level can be essential to prevent disruptions within the supply chain and help to identify "hotspots" and risks associated with industrial resource use. The ESP approach allows for a more realistic assessment of resource availability, provides a good basis for decision making on a corporate or regional level, and complements current (geologic) resource assessment in LCA.

However, several challenges still occur. The assessment is based on current market analyses for individual resources and is strongly time dependent. Furthermore, a limited set of criteria and indicators is assessed in this work, and focus is on the mine production stage only. For sustainable resource management, all life cycle stages, from resource extraction through production and manufacturing to use and end-of-life treatment (Finkbeiner 2011), need to be analyzed. Each stage of the supply chain has to be assessed. Furthermore, a broader set of criteria and indicators have to be assessed for providing a better picture of supply restrictions.

In this study, the supply risk is captured only at a specific point in time providing short- or medium-term results. As mentioned before, the base period of the study can affect value

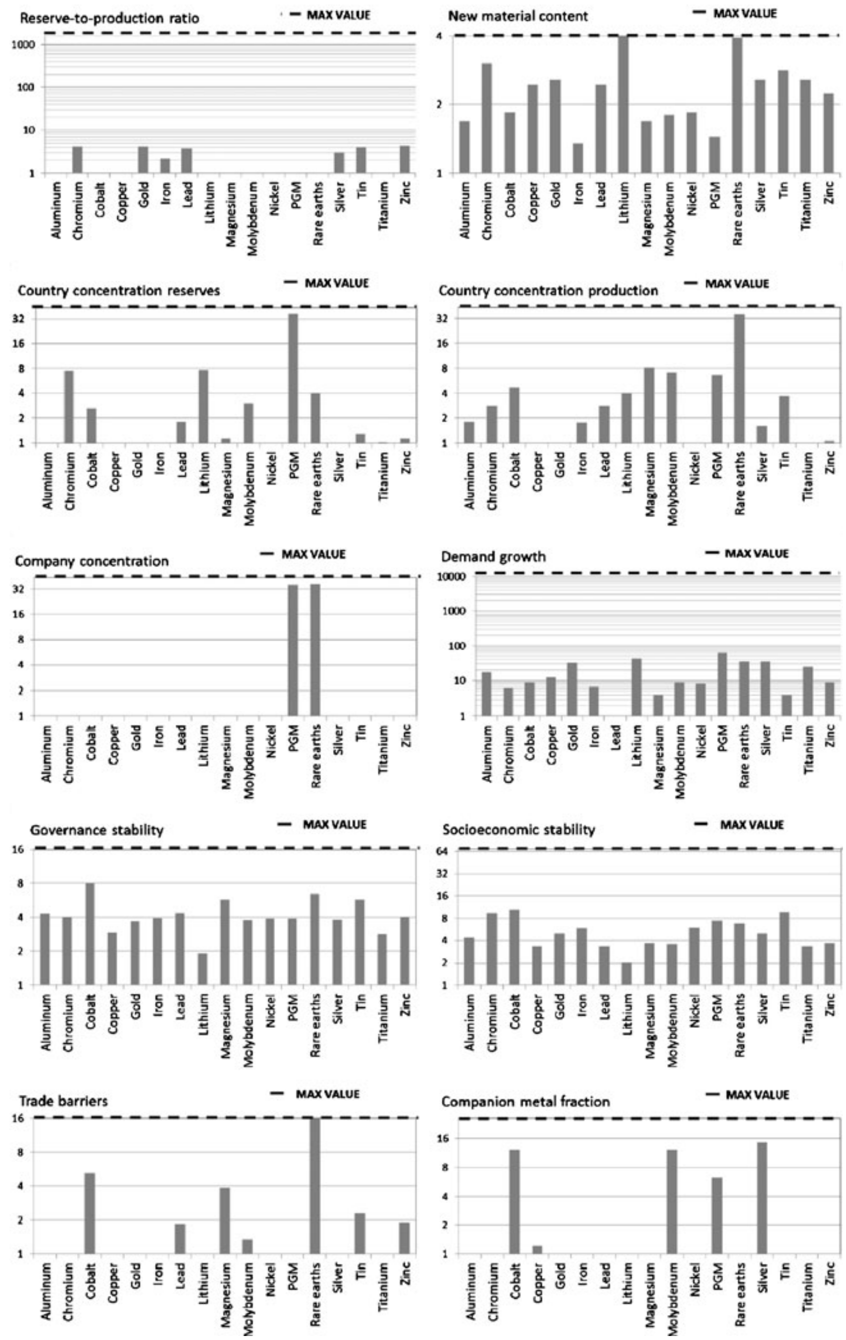


**Fig. 3** $ESP_{global}$: Impact category results in relation to maximum risk value (maximum value is indicated by a black dashed line; values below "1" are associated with no supply risk) (Data based on Angerer et al. 2009a, b; BDI 2010; BGR 2007; CIA 2012; European Commission 2010a; INSG 2012; Nassar et al. 2012; National Research Council 2008; OECD 2009, 2010; POLINARES Consortium 2012; Reuter et al. 2005; The World Bank Group 2012; UNDP 2011; UNEP 2009a, 2011; USGS 2005, 2013)

and relevance of indicators and periodical updates and reconsiderations of data and thresholds are essential.

In addition, future studies need to consider a differentiation of primary and secondary resources. Evaluated criteria mostly refer to primary resource supply only, and some of the developed impact categories are not relevant if only recycled material is used. For the current resource portfolio, the described approach is sufficient, as new material content is high for all resources. However, secondary material, considered as a measure to delay the depletion of primary metal resources, may underlie similar constraints as primary material supply. Thus, a more comprehensive assessment is needed, and primary and secondary materials should be analyzed independently from each other.

Further works will also include the analysis of potential correlations or interrelations of criteria and indicators (to avoid unintended emphasis of certain aspects) and an assessment of temporal sensitivity. Application of this method will be tested further by means of case studies.

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